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MAINTAINING THE THERMAL BALANCE IN MAN

TECHNICAL DOCUMENTARY REPORT AAL-TDR-62-24

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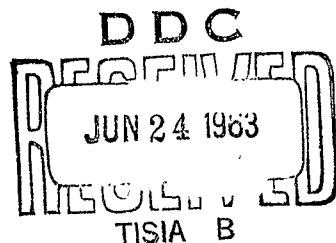
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ARCTIC AEROMEDICAL LABORATORY

AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
FORT WAINWRIGHT, ALASKA

Project 8237-02

(Prepared under Contract AF41(657)-335 by
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ABSTRACT

A report is presented which briefly characterizes the heat production of the human and the heat exchange with the environment. The mechanisms whereby the temperature control system operates are presented. These characteristics are schematically shown in fourteen figures.

PUBLICATION REVIEW

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MAINTAINING THE THERMAL BALANCE IN MAN

This report* briefly characterizes the heat production of the human and the heat exchange with the environment. The sensors, integrator and output of the temperature control system operate within limits as a rather unique parallel system.

While all tissues of the body metabolize and produce heat, some do so at a higher rate than others and some have a capability of greater change in heat production. Certain systems, a small portion of the mass, are slaves to the entire system being necessary as pumps, ventilators, or serving other logistic functions. The heat produced depends on the tissue and its mass. Aschoff and Wever (1958) have presented these characteristics schematically as shown in Figure 1. Some areas like the brain have a high maintenance energy cost and heat production but vary little, while muscle may increase to be the major source of heat. While liver and viscera may increase fivefold, the relative mass does not give this area the importance of muscle. We conventionally think of increases in heat production as due to increased muscular activity, but this is not the sole mechanism.

Just as heat production is not central or uniform, the heat exchange of the body is regional due to geometrical as well as control considerations. The body has a heat capacity which it may use as a source or sink, the peripheral tissues participating more actively than central tissues. Again, the mass of these tissues determines the magnitude of the change. This has led to the use of the words core and shell. It is interesting that, in the human, one-half of the mass is within one inch of the surface. This characteristic of the human body is schematized in Figure 2, where isotherms in the body are drawn for two different temperature conditions. Inserted in this figure is a characterization of the system which brings about these changes -- the circulatory system which by altering convection allows tissues to cool. The extent of cooling can be increased by using large vessels as heat exchangers.

The extent to which the system uses the mechanisms for exchange is summarized in Figure 3. In the lower portion of the figure rectal temperature, average skin temperature and temperatures representative of other areas are shown at various air temperatures. The bars diagrammatically indicate the change in heat content that occurs as the body temperature

* Presented at The Institute of Radio Engineers,
New York City, March 28, 1962.

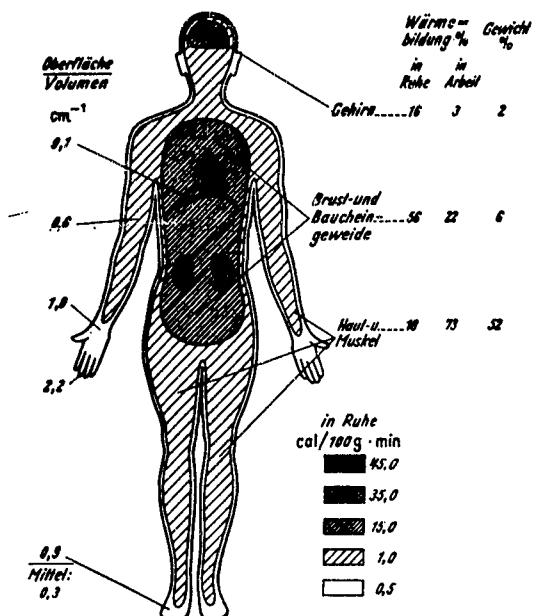


FIGURE 1. Topography of heat production in the core and shell in man. (From Aschoff and Wever, 1958.)

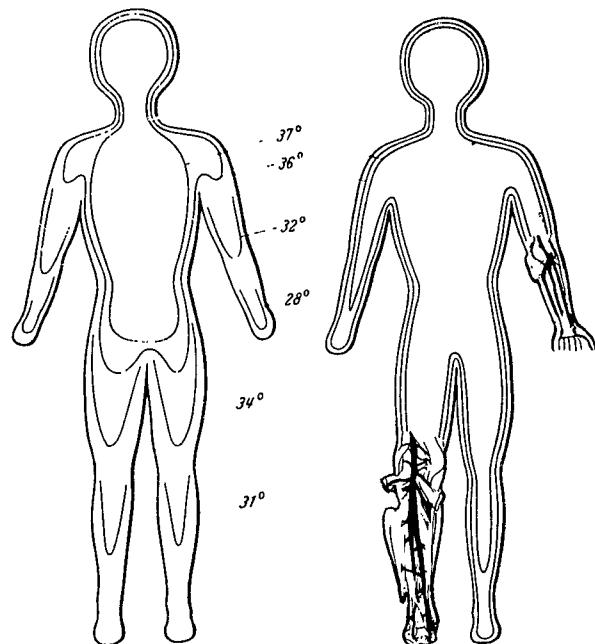


FIGURE 2. Schematic isotherms in body cooling. Warm body on the right, cooler on the left. The insert shows the circulatory system in the leg illustrating the remarkable circulatory arrangement for heat exchanging. (After Aschoff and Wever.)

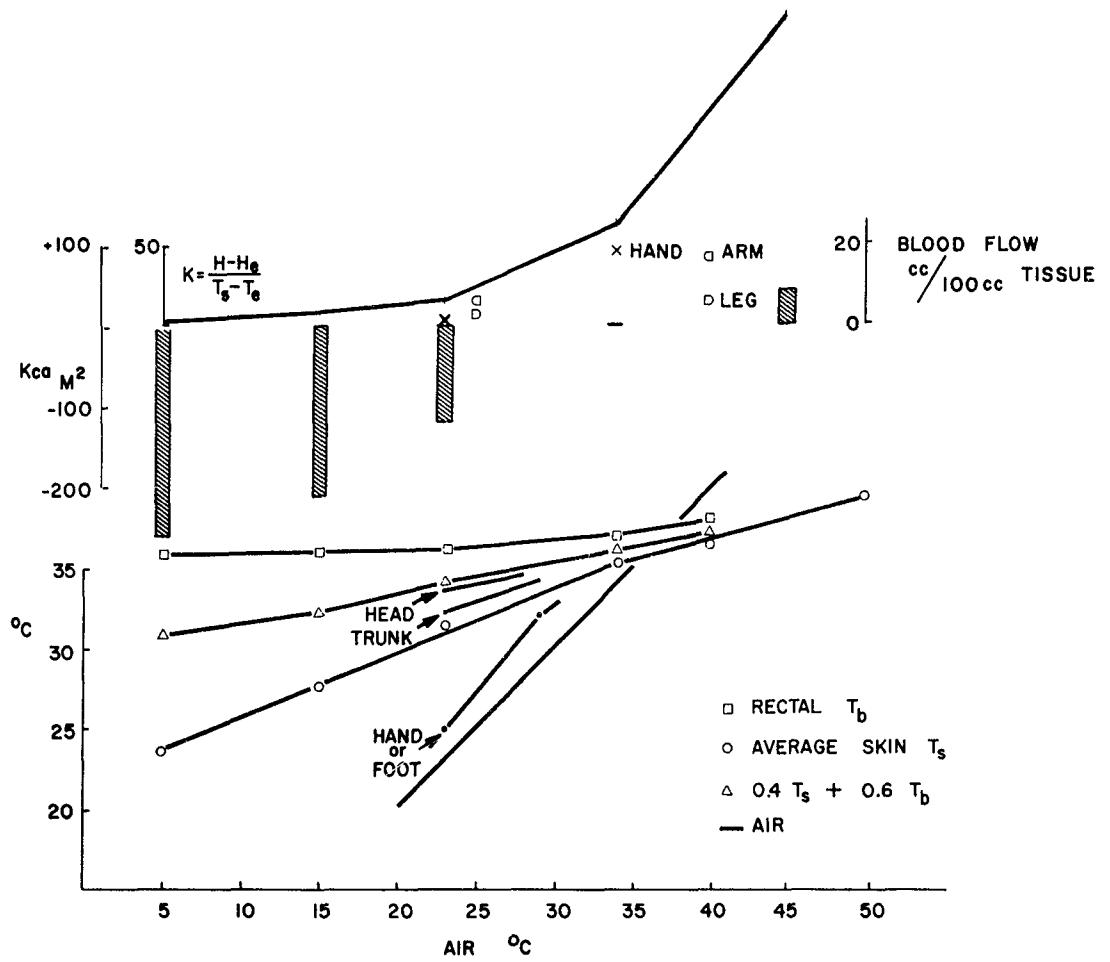


FIGURE 3

Representations from various authors of temperature regulation. In the lower figure the change in rectal temperature, average skin temperature and hand or foot temperature are plotted for various air temperatures. In the bar diagram these data are used to calculate the conductivity and the loss or gain of heat from body tissues. Blood flow in the hand, arm and leg are shown in the insert.

changes. Thus, a deficit of 200 kilocalories or more can accrue by tissue cooling. The upper graph gives some indication of the apparent change in conductivity due to circulatory changes, and specific measures of blood flow in three tissues are shown. An analogue can be constructed to simulate the main events (Figure 4).

The overall response of the heat exchange system has recently been characterized by Benzinger (1961; Benzinger et al, 1961). His results indicate that the mechanisms operative against increase in body temperature are best correlated with brain (cranial) temperature, thus giving this area a primary importance in control (Figure 5). Under negative heat load, however, both peripheral and central temperature are elements in the control system both with respect to heat production and circulation. Heat loss is dependent on internal temperature and skin temperature. The intensity of the metabolic response for any given internal temperature is dependent on the skin temperature (Figure 6).

The control of temperature in the warm-blooded animal is a combined neural and humoral (endocrine) system, but all of the endocrine control is apparently subservient to a neural system. Due to the careful work of Hensel (1952; 1955) the input of this neural control system can be characterized. The technique used in this type of investigation is known as a single fibre analysis and relates the number of impulses on a given fibre to temperature on temperature change. Figure 7 illustrates the technique and Figures 8, 9 and 10 summarize the results of this type of investigation. The impulse rate on any given fibre is related to the rate and extent of change of temperature (Figure 8). The response to a given change in temperature is related to the initial temperature, each fibre having a range in response (Figure 9). Different fibres have a different spectrum of response (Figure 10).

The output of the control system is similar. The calibre of blood vessels changes with the frequency of impulses on the innervating fibres and the amount of muscle activity is related to the frequency of impulses arriving at the neuromuscular junction within limits.

Blood vessels are characterized as resistance and capacitance vessels. In Figure 11 the change in these vessels is shown related to the frequency of impulses. In addition to changes in flow, changes in the volume of blood in the limb also occur. The main vessels in a limb also serve as heat exchangers. The change in flow with temperature is greatest in the skin.

A different type of recording is shown as an illustration of the electrical activity related to muscle motion. In Figure 12 an area in the caudal pons has been stimulated to produce shivering. The electrical activity in muscle

occurs after a delay and persists following the stimulation. Both the delay and the post-stimulatory effects are characteristics of the regulating center not clearly understood.

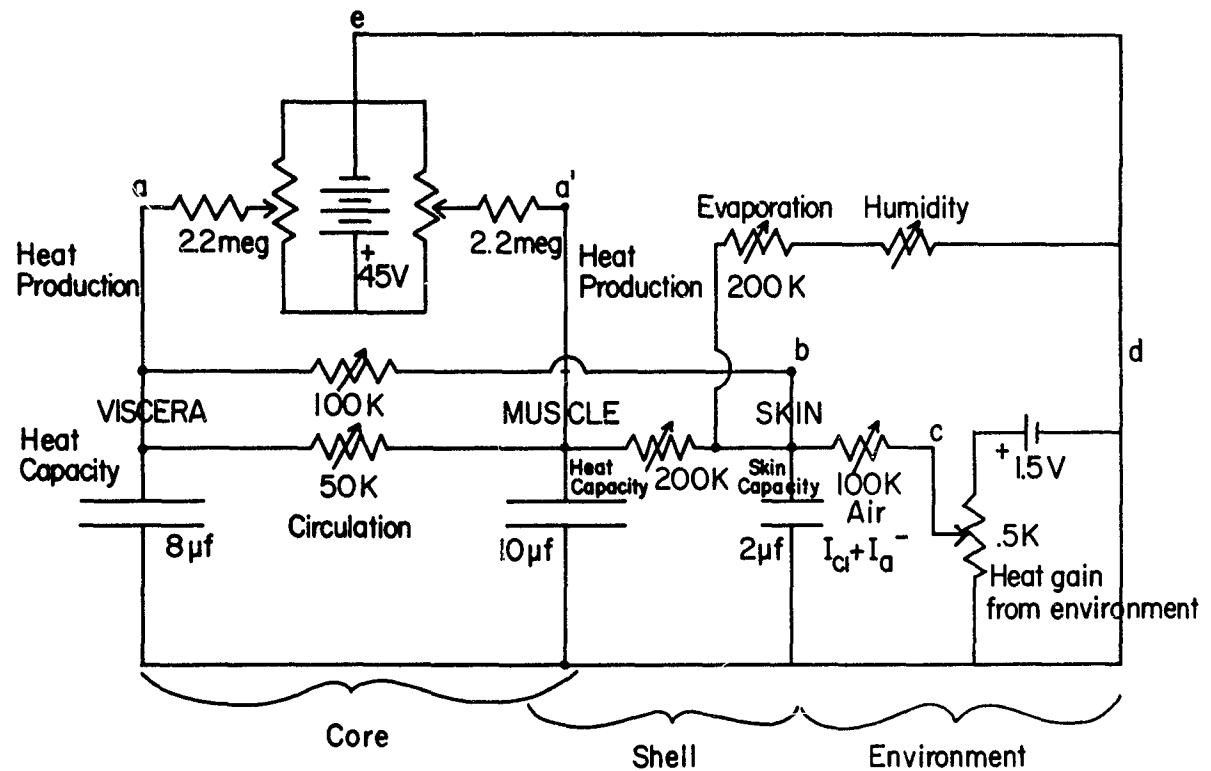


FIGURE 4

Electrical analogue of heat production and heat loss to illustrate the major components of the system.

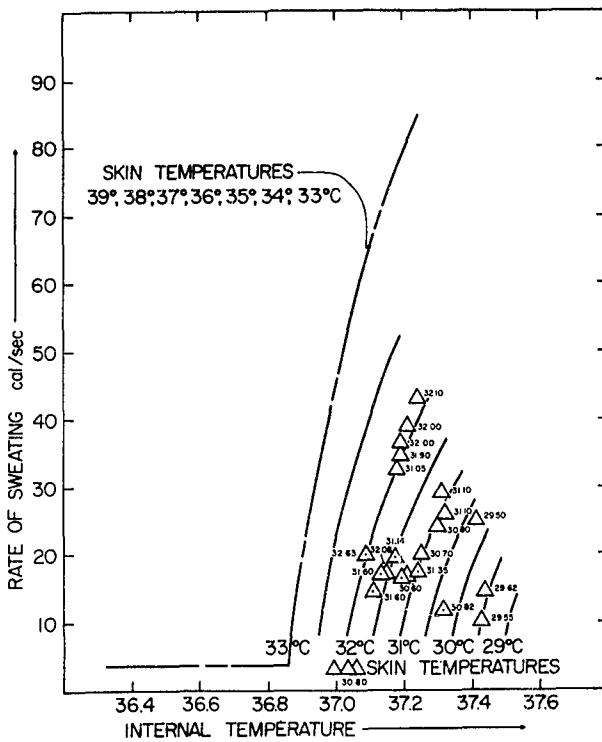


FIGURE 5

Intensity of thermoregulatory sweating during cold reception at the skin. Sweating rates were plotted against internal cranial temperatures. Measurements obtained at similar skin temperatures were connected "best lines." At any given cranial internal temperature, sweating rates are seen to be diminished by approximately 40 cal/sec for every degree C decrease in level of skin temperature. This figure contains no resting observations as these paradoxical conditions cannot be produced in steady states at rest. Work rates were mechanically equivalent to 6 cal/sec (Δ) or 11 cal/sec (\triangle), respectively. Increase in work rate enlarges the range of observations to the right (low skin, with high internal temperature). Experiments were carried out between April 4 and June 5, 1961, with one subject, D. D., nude, age 26, weight 88.6 kg, height 176 cm. (From Benzinger et al, 1961.)

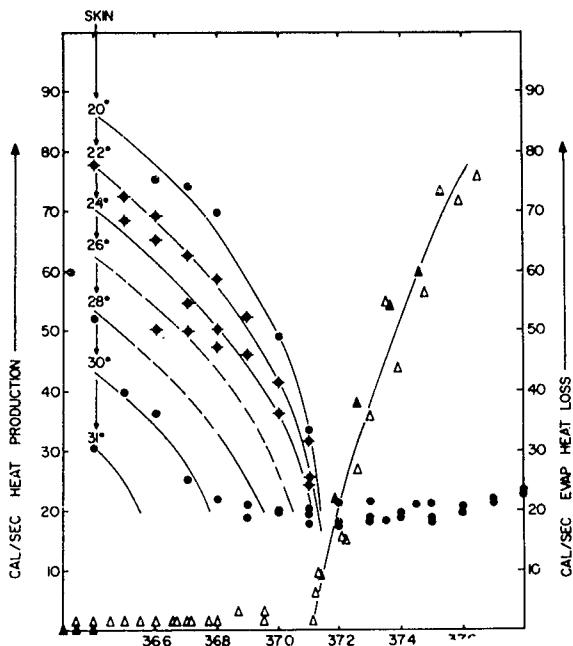


FIGURE 6

Experimental resolution of "chemical" and "physical" temperature regulation. Thermoregulatory heat production (abscissae, circles, cal/sec) at low and constant cranial internal temperature (ordinates) is determined by steady cold-stimulation of skin (temperatures 31° to 20° C). Central warm-stimulation (ordinates) leads to depressing counteraction, which becomes complete at individual "set-point of thermostat," 37.1° C. Thermoregulatory sweating (triangles, abscissae) is uniquely determined by internal sensory warm-reception. It begins at setpoint, rises to comparable evaporative loss (cal/sec). Result is tenacious maintenance of setpoint (homeostasis) over four-fold range of production or losses.

Note: For narrow temperature range on ordinate, resolving power of classical methods was insufficient. (From Benzinger, 1961.)

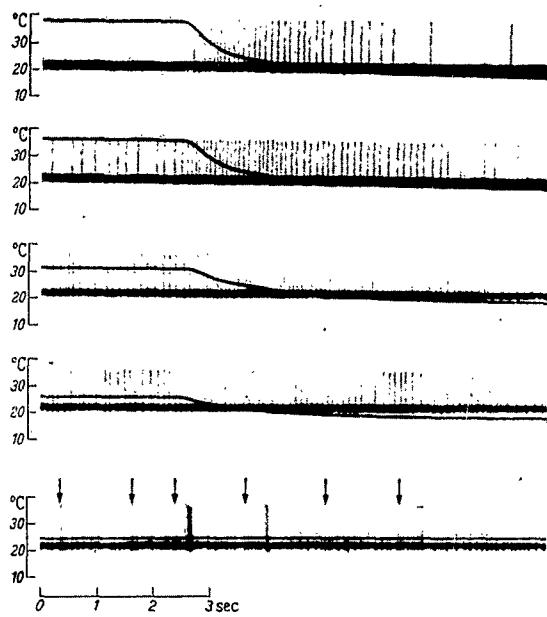


FIGURE 7. Change in impulse frequency with cooling of the skin. (Witt and Hensel, 1959.)

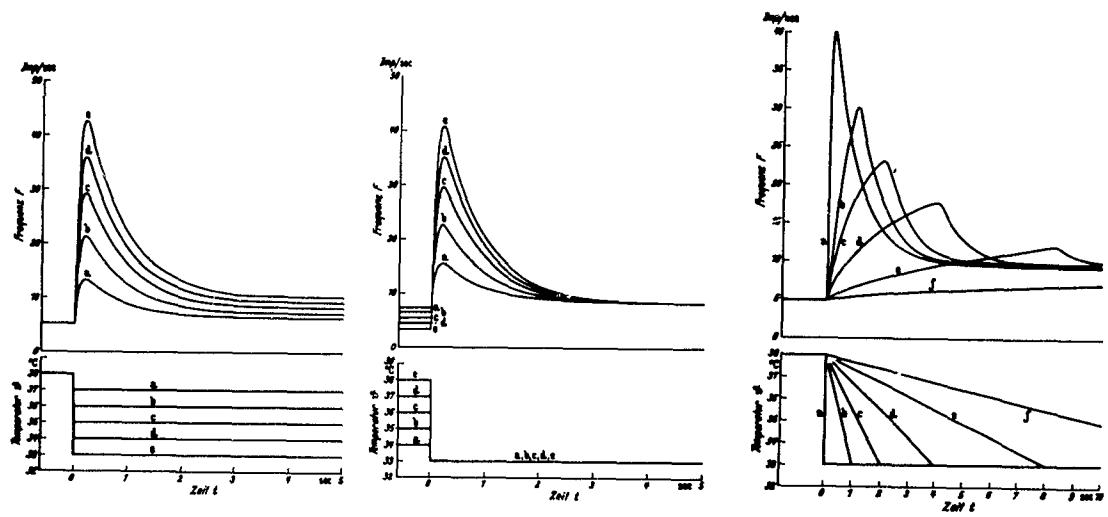


FIGURE 8. Relationship of impulse frequency to temperature and rate of change of temperature. (Hensel, 1952.)

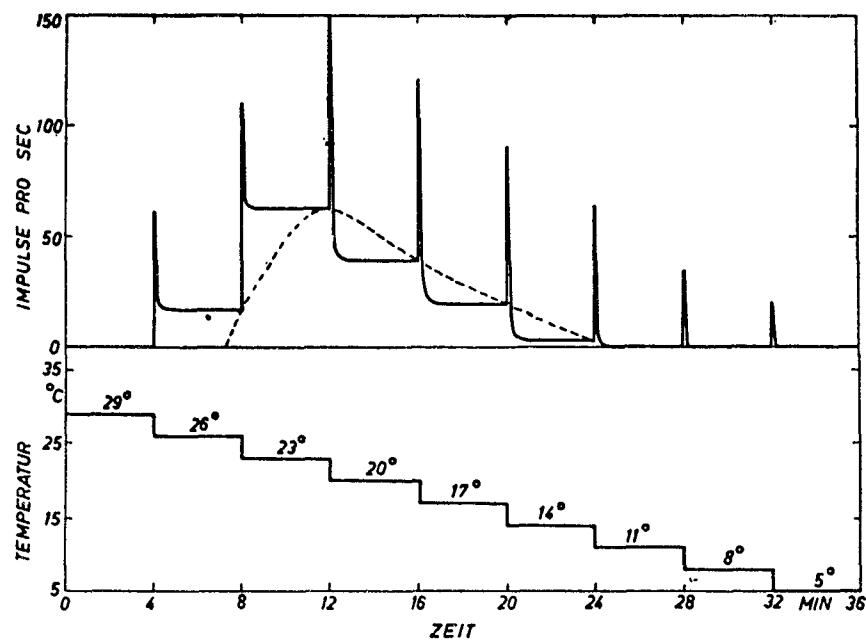


Abb. 4. Impulsfrequenz einer Einzelfaser der isolierten Mandibularampullen von *Scyllium* bei einer Stufenfolge von Kältesprüngen von 29° bis 5° . Die gestrichelte Kurve stellt das Verhalten der stationären Dauerentladung als Funktion der Temperatur dar.

FIGURE 9

Impulse frequency of a single fibre with changes in temperature.
(Hensel, 1955.)

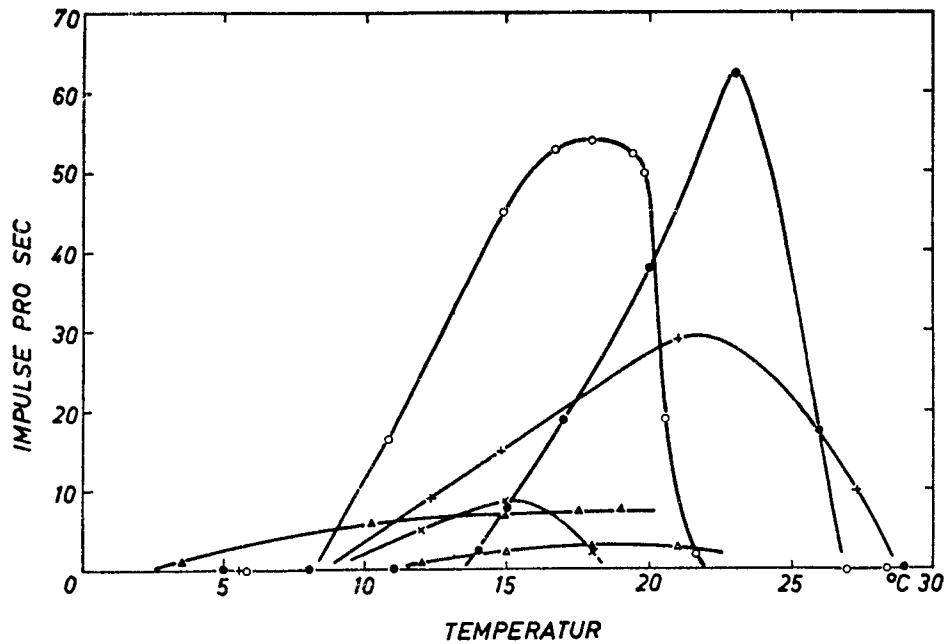


Abb. 2. Stationäre Impulsfrequenzen verschiedener Einzelfasern als Funktion der Temperatur. Isolierte Mandibularampullen von *Scyllium*.

FIGURE 10

Stationary impulse frequency of different fibres as a function of temperature. (Hensel, 1955.)

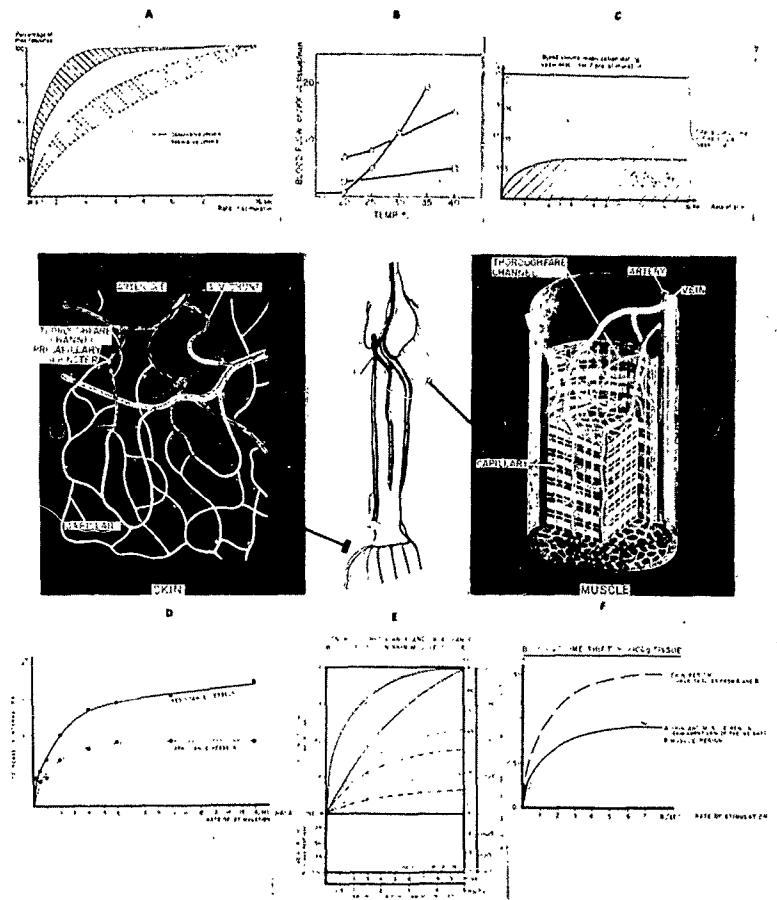


FIGURE 11

Response of resistance and capacitance vessels of skin and muscle as a function of rate of stimulation and related to blood volume of the limb. Upper left figure indicates percent of response related to impulse frequency, lower left the decrease in radius. Right-hand figures indicate the blood volume shift. In the lower center figure the neural effect is compared to a humoral effect. Actual blood flows at different temperatures are given in the upper center figure for hand, O, leg, □ and arm, Δ. Capacitance and resistance curves from Melander (1960).

Our knowledge of the systems involved in maintaining thermal balance is characterized schematically in Figure 13. Sense organs are distributed differently in different areas of the body. The overall effect appears related to the number, the temperature and rate of change of temperature. Counting seems the simplest handling system for these. The stat itself is sensitive to temperature and to the input from the periphery. An activator is a necessary postulate for delays and for the effect of other inputs.

In more anatomical terms (Figure 14) the temperature regulation center is in the hypothalamus. The functions of loss and conservation are to some extent separate. This area of the brain has many inputs other than temperature. Temperature fibres are traceable to the thalamus. The interconnection to the hypothalamus is certainly present but not clearly delineated. Two separate outputs are indicated, one related to blood vessel calibre and consequently heat transport and heat content, the other related to heat production by muscle action. Studies on acclimation to cold have indicated the presence of a nonshivering thermogenic system under the control of the sympathetic nervous system. In addition, rather marked changes take place in the mitochondrial systems involved in energy production and in the metabolic response to adrenaline and noradrenaline (Carlson, 1962a; 1962b).

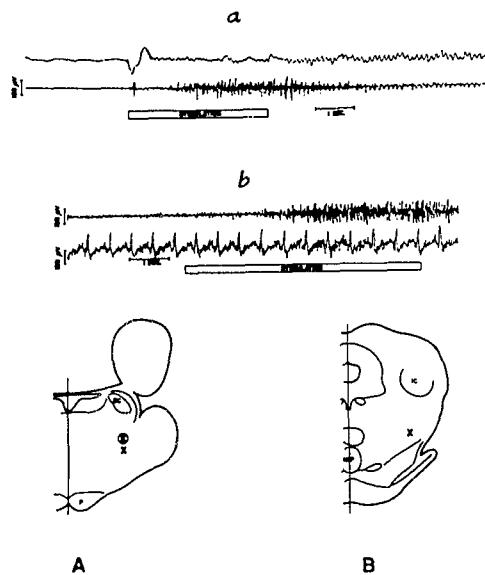


FIGURE 12. A: Cross-section through caudal pons of cat 31, showing stimulation points (X). B: Cross-section through pons of cat 30, showing stimulation point (X). a: Top tracing - mechanogram; bottom - electromyogram of shivering obtained during stimulation of encircled X in A. b: Top tracing - electromyogram from hind leg; bottom - electrical record from intercostals during shivering produced by stimulation of point X in B. (Birzis and Hemingway, 1957.)

TEMPERATURE REGULATION

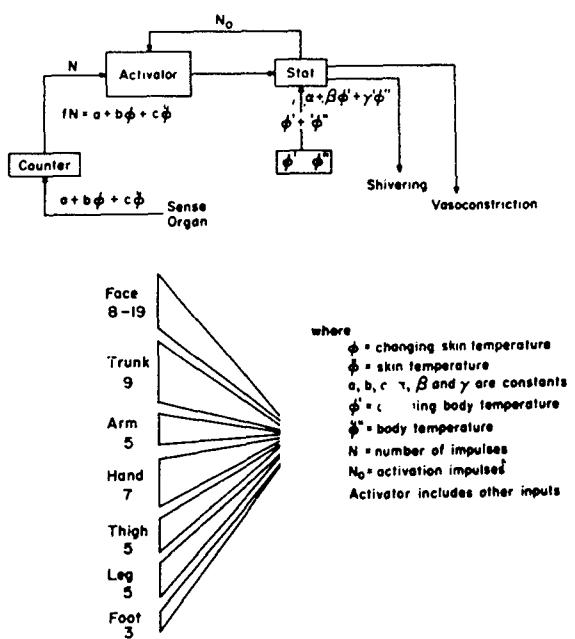


FIGURE 13. Schematic of temperature regulation.

Our knowledge of the systems involved in maintaining thermal balance is characterized schematically in Figure 13. Sense organs are distributed differently in different areas of the body. The overall effect appears related to the number, the temperature and rate of change of temperature. Counting seems the simplest handling system for these. The stat itself is sensitive to temperature and to the input from the periphery. An activator is a necessary postulate for delays and for the effect of other inputs.

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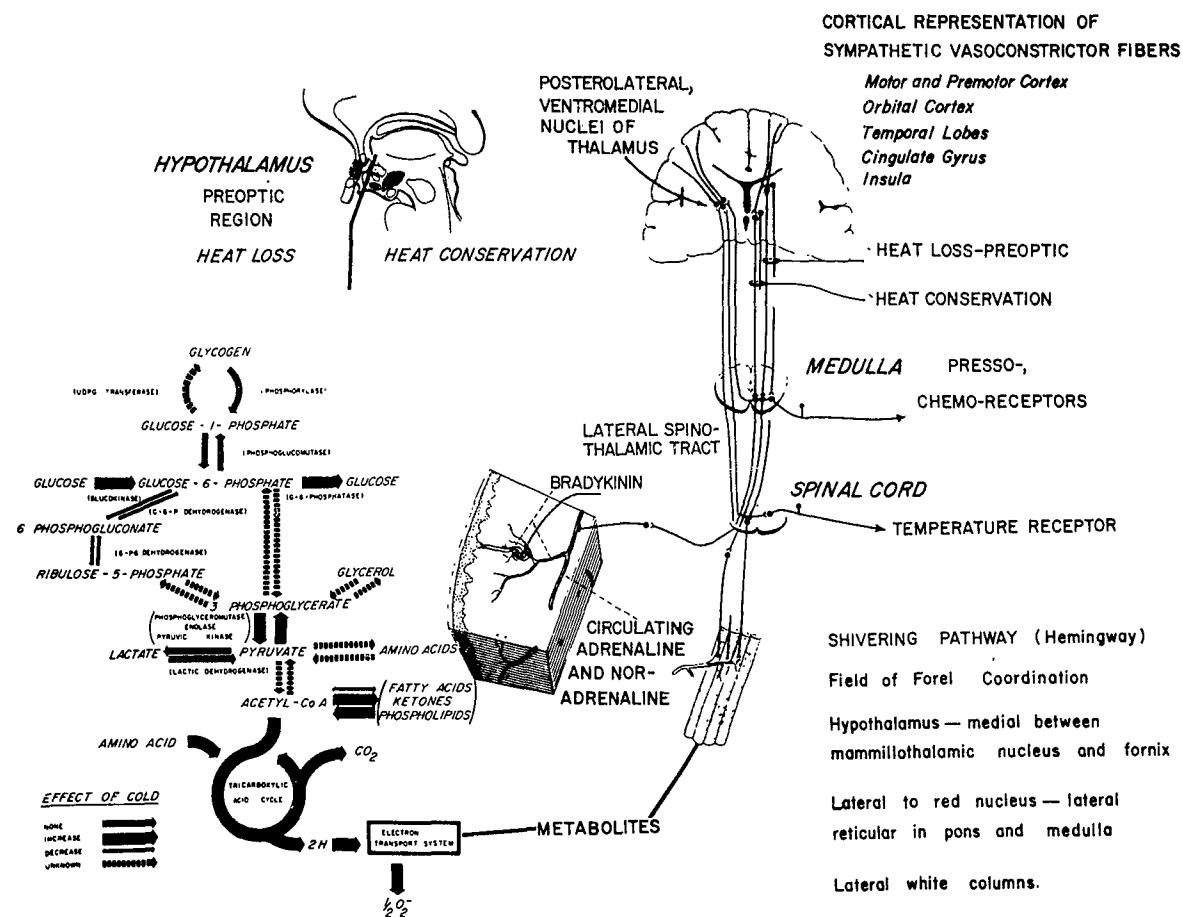


FIGURE 14

Main neural factors in temperature regulation and the metabolic systems involved in the response.

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